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A Novel Compact Quadruple-Band Indoor Base Station Antenna for 2G/3G/4G/5G Systems

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ABSTRACT This paper presents a quadruple-band indoor base station antenna for 2G/3G/4G/5G mobile communications, which covers multiple frequency bands of 0.8 – 0.96 GHz, 1.7 – 2.7 GHz, 3.3 – 3.8 GHz and 4.8 – 5.8 GHz and has a compact size with its overall dimensions of 204 × 175 × 39 mm^3. The lower frequency bands over 0.8 – 0.96 GHz and 1.7 – 2.7 GHz are achieved through the combination of an asymmetrical dipole antenna and parasitic patches. A stepped-impedance feeding structure is used to improve the impedance matching of the dipole antenna over these two frequency bands. Meanwhile, the feeding structure also introduces an extra resonant frequency band of 3.3 – 3.8 GHz. By adding an additional small T-shaped patch, the higher resonant frequency band at 5 GHz is obtained. The parallel surrogate model-assisted hybrid differential evolution for antenna optimization (PSADEA) is employed to optimize the overall quadruple-band performance. We have fabricated and tested the final optimized antenna whose average gain is about 5.4 dBi at 0.8 – 0.96 GHz, 8.1 dBi at 1.7 – 2.7 GHz, 8.5 dBi at 3.3 – 3.8 GHz and 8.1 dBi at 4.8 – 5.0 GHz respectively. The proposed antenna has high efficiency and is of low cost and low profile, which makes it an excellent candidate for 2G/3G/4G/5G base station antenna systems.

INDEX TERMS 2G/3G/4G/5G, base station antenna, compact antennas, optimization method, quadruple-band antennas.

I. INTRODUCTION

The performance of mobile wireless communication systems would be degraded in indoor environments, undergrounds and tunnels. Special indoor base station antennas are required for these areas in order to improve the quality and performance of mobile communication systems [1]. In particular, multiband antennas with a relatively compact dimension that can cover 2G, 3G and 4G frequency bands (0.8 – 0.96 GHz and 1.7 – 2.7 GHz) are preferred for many indoor base stations. With the rapid growth of communication data capacity, the fifth-generation (5G) communication systems are being deployed from this year (2019) in many countries. Since 2016, the band from 3.4 – 3.8 GHz has been allocated for 5G trials in European Union (EU). China's Ministry of Industry and Information Technology (MIIT) announced that 3.3 – 3.4 (indoor only), 3.4 – 3.6 and 4.8 – 5.0 GHz bands were allocated for 5G services in 2017 [2]. Considering the extra 5G bands, it may bring significant challenges in designing the next-generation indoor base station antennas. For example, it will increase the complexity and physical dimension of the antenna after adding the 5G bands in together with the well-developed 2G/3G/4G band coverage. Therefore, a compact multiband antenna with wide frequency bands is preferred for base station applications to support 2G, 3G, 4G and 5G communication systems simultaneously without increasing the overall size and number of antennas. In other words, the new indoor base station antenna is required to cover the frequency bands of 0.8 – 0.96, 1.7 – 2.7, 3.3 – 3.8 and 4.8 – 5.0 GHz with a compact size and low profile.

In the last twenty years, a large number of base station antennas with different structures have been investigated and proposed. Compared with monopole antennas, dipole antennas are more attractive for base stations, because it is easier to provide dual-polarization (e.g., crossed dipole), which can increase system capacity and combating the issue of

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multipath fading [3]. A number of broadband dual-polarized dipole antennas have been developed for 2G/3G/4G systems operating in the band 1.71 – 2.69 GHz [4]–[10]. The broadband performance can be achieved by many methods, such as making slots on the radiating patch [4], [5], adding parasitic elements [5], [6], using shared-dipole structure [7], [8], or applying better feeding methods [9], [10]. In fact, multiband antennas could perform better than wideband antennas due to in-band interference for such applications. Therefore, many dual-broadband antennas have been proposed to cover both 0.8 – 0.96 GHz and 1.7 – 2.7 GHz [11]–[16]. To achieve the dual-band characteristics, the first way is to share an element for the lower band and upper band [11]; the second way is to use the different elements for the lower band and upper band which is often used for base station [12]–[16]. The second way is easier to adjust the down-tilt angles in the lower band and upper band, but the structure will become more complicated compared with the first way. At the moment, very few published papers have reported the triple-band base station antennas for 5G due to the design complexity [17].

To obtain the desired performance, antenna optimization is often an essential step. However, optimizers in existing commercial electromagnetic (EM) simulation tools have difficulties to achieve the desired performance for this antenna because of the complexity of the structure. Therefore, the parallel surrogate model-assisted differential evolution method for antenna synthesis (PSADEA) [18] is selected to optimize this antenna. PSADEA is the state-of-the-art in the SADEA algorithm family [18]–[21], while the first generation SADEA method [20] already showed clear advantages over popular antenna optimization methods and tools [22].

Compared to standard global optimization methods, the SADEA algorithm family is able to obtain better design quality and offers 3 to 20 times efficiency improvement [20]–[22]. The primary features in the SADEA algorithm family include differential evolution (DE) algorithm as the global search engine, Gaussian process as the machine learning technique for surrogate modeling and the surrogate model-aware evolutionary search framework [23] as the model management method. PSADEA is distinct from other SADEA versions through the complementary adoption of multiple DE mutation operators and reinforcement learning techniques to achieve an additional 1.5 to 3 times efficiency improvement and higher design solution quality even in the sequential mode [18], [19]. However, the whole base station antenna involves more than 40 design parameters and more than 10 specifications. Thus the time spent on Gaussian process surrogate modeling in PSADEA becomes long. To address this problem, design knowledge is used to separate the design parameters, and PSADEA is used to focus on 19 design parameters. A successful design is finally obtained.

Furthermore, in this paper, a compact quadruple-band indoor base station antenna is proposed. It covers 0.8 – 0.96 GHz, 1.7 – 2.7 GHz, 3.3 – 3.8 GHz and 4.8 – 5.0 GHz simultaneously, which means that it can support 2G/3G/4G/5G systems at the same time. Meanwhile, through the folded stepped impedance feeding structure, the antenna has a compact size, especially the height, which is only $204 \times 175 \times 39$ mm^3. In addition, the radome of the antenna is also considered for practical applications.

The paper is organized as follows: Section II describes the geometry, components and fabrication of the proposed antenna. Section III illuminates the evolution of the proposed antenna. The measurement process and results are shown in Section IV. The conclusion is drawn in Section V.

II. ANTENNA STRUCTURE

The outer structure of the proposed antenna is shown in Fig. 1, which is made of polyvinyl chloride (PVC) box (with relative permittivity $\varepsilon_r = 3$) and an aluminum reflector. The thicknesses of the PVC box and aluminum reflector are 2 mm and 1 mm respectively. Fig. 2 illustrates the inner structure of the proposed antenna, which looks complicated but is based on dipole antenna (to be discussed in next section). Twenty-one blue PVC cylinders are applied to support the aluminum structure and provide the essential gap distance between the different components. They also provide a robust structure of the antenna. In order to have a better understanding of the inner structure, it can be divided into four layers and four bent metal strips, as shown in Fig. 3. The first layer consists of three metal patches and two metal strips, which are parasitic and used to increase the bandwidth of the first and second band. The second layer includes three metal patches and one feeding structure; the third layer includes one metal patch and one feeding structure. For these two layers, the metal patches are concatenated to the feeding structures through trapezoid aluminum to form a whole. The height of the two trapezoids is different. Therefore, it can control the gap distance between the two layers. The second layer and third layer are the main components of the proposed antenna. They are two arms of a dipole antenna with the feeding structure. The feeding structure is connected to a 50 Ω coaxial cable. The outer of the coaxial cable is connected to the feeding structure of the second layer, and the inner of the coaxial cable is connected to the feeding structure of the third layer. Normally, the feeding

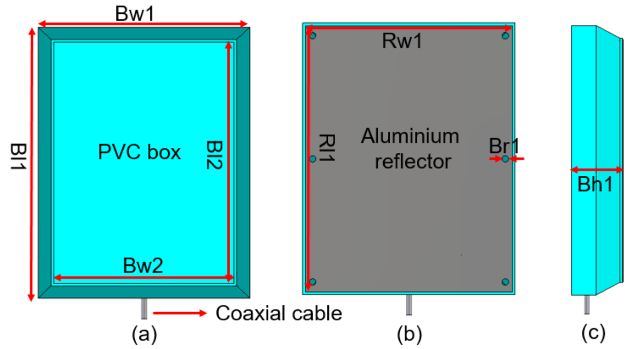

FIGURE 1. The outer structure of the proposed antenna. (a) Front view. (b) Back view. (c) Side view.

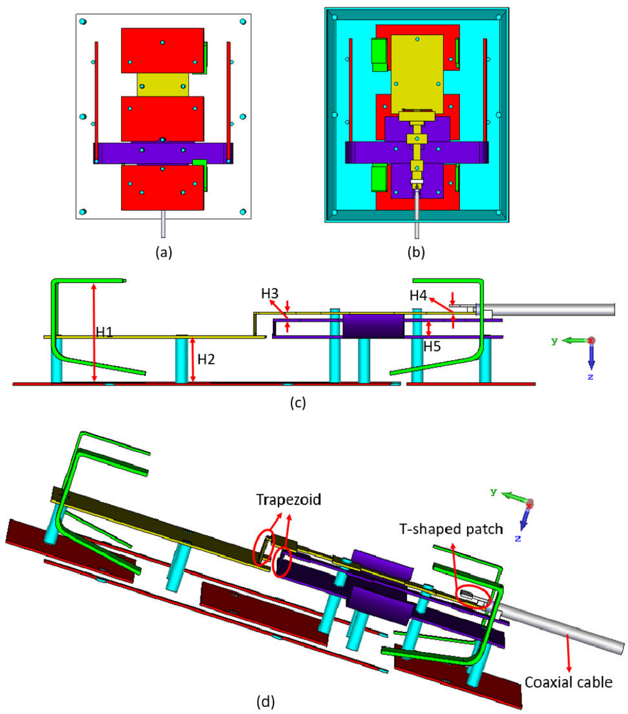

FIGURE 2. The inner structure of the proposed antenna. (a) Front view (without box). (b) Back view (without reflector). (c) Side view (without box and reflector). (d) Side view (without box and reflector).

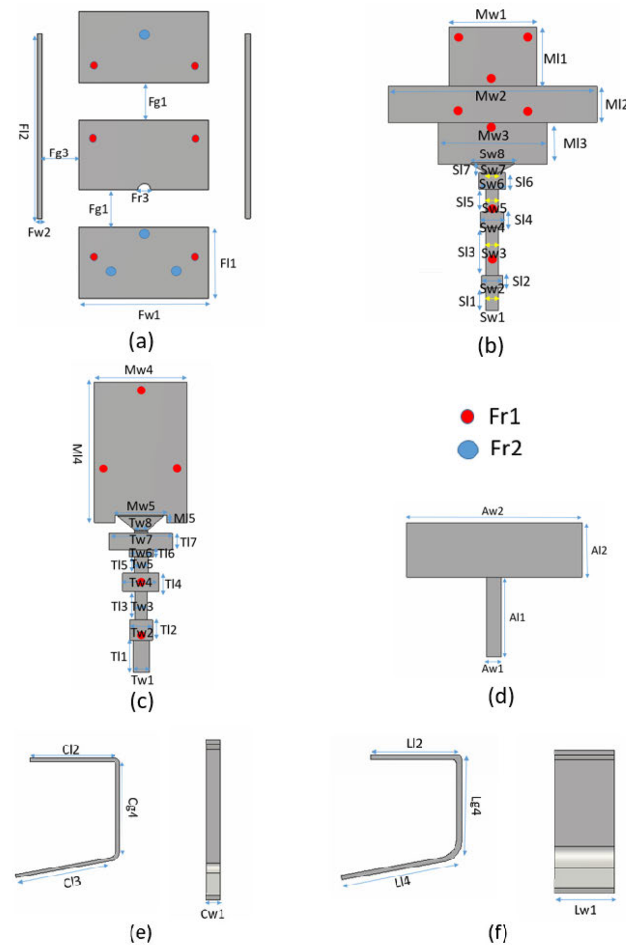

FIGURE 3. The detailed structure of the proposed antenna. (a) First layer. (b) Second layer. (c) Third layer. (d) Fourth layer. (e) Side and front view of the thin bent metal strip. (f) Side and front view of the thick bent metal strip.

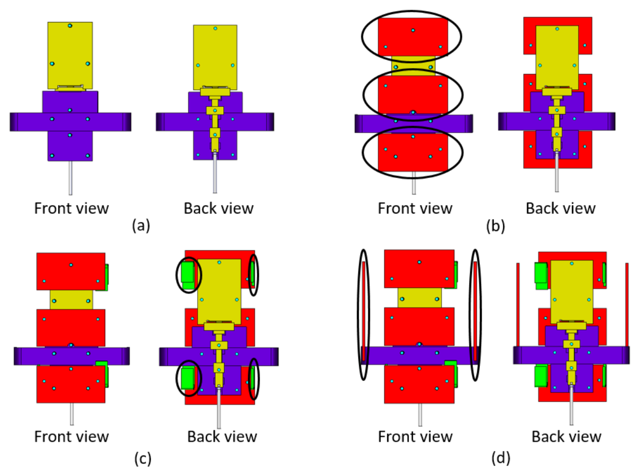

FIGURE 4. The evolution of the dual-band antenna. (a) Front and back view of antenna 1. (b) Front and back view of antenna 2. (c) Front and back view of antenna 3. (d) Front and back view of dual-band antenna.

structure is perpendicular to the dipole antenna. However, in this design, the feeding structure is folded and is made parallel to the dipole to minimize the height of the whole antenna. In addition, both ends of the long metal patch in the second layer are bent by 90 degrees to increase the coupling between the first layer and the second layer. The fourth layer is a small T-shaped patch, which is employed to introduce a resonant frequency for the higher frequency band. It is welded to the inner of the coaxial cable through a piece of aluminum. All the four layers are fabricated with 0.8 mm aluminum. The four metal strips are fixed to the reflector by screws and nuts. They are also bent to minimize the height of the antenna. The two thin bent metal strips are made of 0.8 mm aluminum and the two thick bent metal strips are made of 1.2 mm aluminum. In this design, we choose to use aluminum instead of copper due to its low cost, lightweight and highly malleable. The PVC box and cylinders are printed by 3D-Printing technology. Meanwhile, all the aluminum structures are cut by a laser-cutting machine. The detailed dimensions of the proposed antenna are presented in Table 1 which are optimized dimensions as we will discuss later.

III. EVOLUTION OF THE PROPOSED ANTENNA

The general evolution process includes two stages. The first stage is to cover the three lower bands up to 3.8 GHz. The design process is systematic, and some design parameters can be obtained as follows.

Initially, Antenna 1 was a simple dipole antenna. The two arms of the dipole antenna were made different to achieve more resonant frequencies. Then, the stepped impedance feeding structure was used to feed the antenna as shown in Fig. 4. As mentioned before, the feeding structure was

TABLE 1. Dimensions of the proposed antenna.

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
Bl1	204	Mw1	50	Tl1	17
Bl2	185	Ml1	33.5	Tw1	8.6
Bw1	175	Mw2	118.4	Tl2	10.8
Bw2	160	Ml2	20	Tw2	12.1
Br1	5	Mw3	62	Tl3	15.2
Bh1	39	Ml3	24	Tw3	6.5
Rw1	170.6	Mw4	50	Tl4	9.6
Rl1	200	Ml4	75	Tw4	19.9
H1	34	Mw5	28	Tl5	8.5
H2	15.2	Ml5	4	Tw5	7.4
H3	1.6	Sl1	12.7	Tl6	3.8
H4	1.7	Sw1	7	Tw6	17.9
H5	4.8	Sl2	7	Tl7	8.8
Fl1	43.5	Sw2	11.9	Tw7	34.3
Fw1	80	Sl3	27.2	Tw8	7
Fl2	114	Sw3	7	Cl2	23
Fw2	3	Sl4	9	Cl3	26.3
Fg1	23	Sw4	13	Cg4	24.33
Fg3	22.5	Sl5	12.7	Cw1	2.7
Fr1	1.7	Sw5	7	Ll2	23
Fr2	2	Sl6	9.4	Lg4	21.8
Aw1	1	Sw6	14.9	Ll4	27.9
Al1	5.4	Sl7	4.8	Lw1	13.8
Aw2	11.9	Sw7	7		
Al2	3.7	Sw8	24.9		

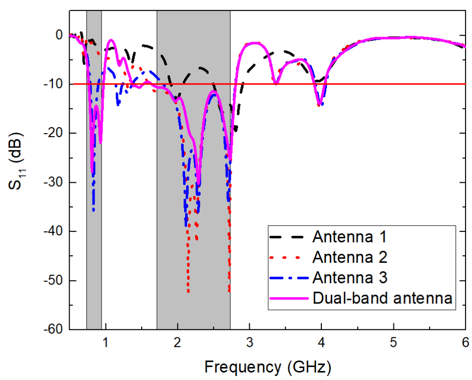

FIGURE 5. The reflection coefficient of the four reference antennas.

folded to minimize the height of the antenna. The performance of Antenna 1 is shown in Fig. 5. It is apparent that Antenna 1 has many resonant frequencies, but the bandwidth is narrow. To widen the bandwidth, three aluminum patches were added on the top of the dipole and fixed by the PVC cylinders. They help to widen the bandwidth through coupling between the dipole and three aluminum patches. Therefore, the frequency band 1.7 – 2.7 GHz was achieved. The reflection coefficient of Antenna 2 shows no resonant frequency between 0.8 - 0.96 GHz. As a result, two thick bent metal strips and two thin bent metal strips were introduced to solve this problem, as shown in Fig. 4. However, as shown in Fig. 5, the bandwidth of the first band was not wide enough to cover 0.8 – 0.96 GHz for $S_{11} < -10$ dB. Another two metal strips were introduced to widen the bandwidth. In the end, a dual-band antenna was achieved, which covers

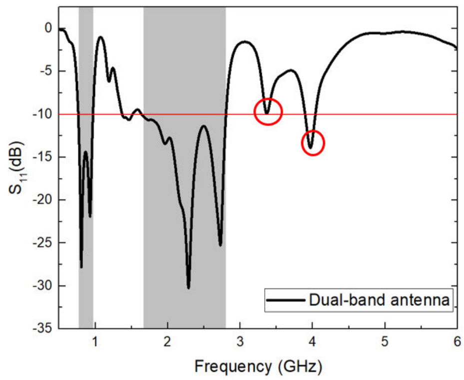

FIGURE 6. The reflection coefficient of the dual-band antenna.

0.8 – 0.96 GHz and 1.7 – 2.7 GHz, as shown in Fig. 6. It is easy to find there are two resonant frequencies between 3 and 4 GHz. This means it is possible to realize the band 3.3 – 3.8 GHz through impedance matching. The stepped impedance feeding structure was applied to feed the antenna for the lower frequency band, and it can be used to radiate for the higher frequency band. According to the theory of half-wavelength dipole, the most sensitive parameter for the band 3.3 – 3.8 GHz is Tw4 as shown in Fig. 7. Fig. 8 illuminates that the resistance becomes smaller, and the impedance matching for the band 3.3 – 3.8 GHz becomes better with the increase of Tw4. After few steps of manual tuning, the triple-band performance was achieved as shown in Fig. 9.

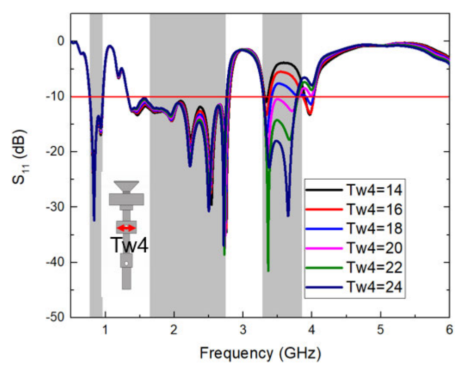

FIGURE 7. The reflection coefficient of the Tw4 with different length.

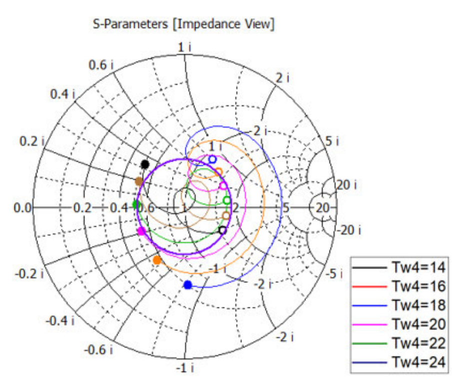

FIGURE 8. The effect of the Tw4 with different length in Smith chart.

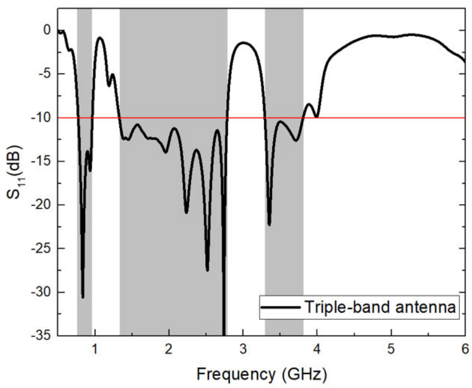

FIGURE 9. The reflection coefficient of the triple-band antenna.

The goal of the second stage is to keep the current performance of the three bands at lower frequency ranges and introduce a new resonant frequency for the higher band. Hence, a small T-shaped aluminum patch was put on the top of the feeding structure, and it was soldered with the coaxial cable by a small piece of aluminium. The performance of the antenna is shown in Fig. 10. Then, the task becomes optimizing parameters of the small T-shaped patch and the feeding structure (third layer) to achieve the desired performance of all bands.

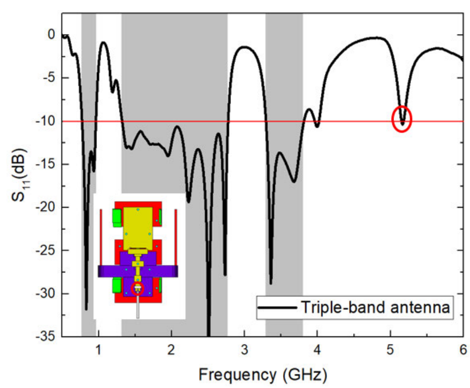

FIGURE 10. The reflection coefficient of the triple-band antenna plus small T-shaped patch.

This optimization task is difficult and the widely used local optimizers (e.g., Trust Region Framework in CST Microwave Studio) were firstly employed, but the results were far from satisfactory. Existing global optimizers (e.g., particle swarm optimization) are estimated to cost prohibitive time without a guarantee of success. Therefore, as said in Section I, the state-of-the-art method, PSADEA [1], was used. By using design knowledge to ignore many design parameters for the three bands at lower frequency ranges, the number of critical design parameters were reduced to 19 (Tl1, Tw1, Tl2, Tw2, Tl3, Tw3, Tl4, Tw4, Tl5, Tw5, Tl6, Tw6, Tl7, Tw7, Tw8, Aw1, Al1, Aw2 and Al2). They were optimized to adjust the coupling between the T-shaped patch resonator and the feeding structure of the antenna. The optimization goal is the minimization of the maximum return loss in the newly introduced band (4.8 – 5.0 GHz) subject to having a maximum return loss of less than or equal to -10 dB in the existing bands (i.e. 0.8 – 0.96 GHz, 1.7 – 2.7 GHz and 3.3 – 3.8 GHz). After three days' optimization, PSADEA produced a design with the frequency response shown in Fig. 11, which has met the return loss requirement across all the four bands for sub – 6 GHz 5G operations that is, it covers 0.8 – 0.96, 1.7 – 2.7, 3.3 – 3.8 and 4.8 – 5.0 GHz.

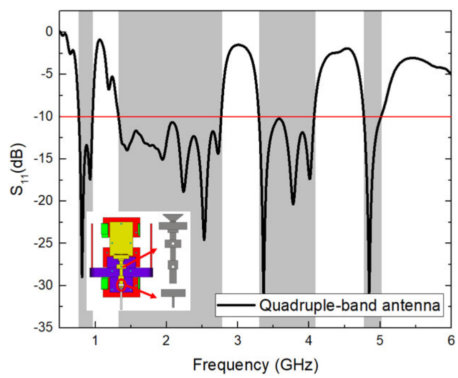

FIGURE 11. The reflection coefficient of the quadruple-band antenna.

IV. THE PROPOSED ANTENNA RESULTS

In order to verify the simulation results, the proposed quadruple-band indoor base station antenna was fabricated and measured, as shown in Fig. 12. The simulation results were obtained using CST microwave studio. Fig. 13 depicts the setup of the measurement; it is accomplished in an anechoic chamber using a Vector Network Analyzer (VNA). Finally, the measurement results of the reflection coefficient, gain and radiation pattern are obtained. The antenna radiation efficiency was obtained using a reverberation chamber.

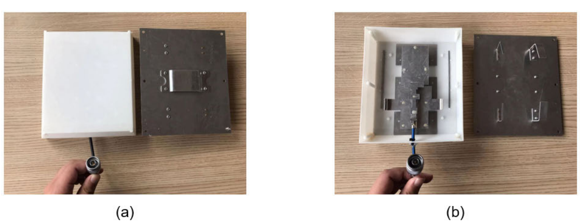

FIGURE 12. A prototype of the proposed antenna. (a) Outer view. (b) Inner view.

Fig. 14 illuminates the simulated and measured reflection coefficient. It shows a good agreement between the simulated and measured results. For VSWR ≤ 2, the measured impedance fractional bandwidths are 22% (0.77 – 0.96 GHz), 71.8% (1.32 – 2.8 GHz), 21.6% (3.3 – 4.1 GHz) and 4.3% (4.79 – 5.0 GHz) for B1, B2, B3 and B4 respectively.

The simulated and measured realized gains are shown in Fig. 15, where a good agreement between them is observed. The average gain for each band is 5.4 dBi (0.8 – 0.96 GHz), 8.1 dBi (1.7 – 2.7 GHz), 8.5 dBi (3.3 – 3.8 GHz) and 8.1 dBi (4.8 – 5.0 GHz), respectively.

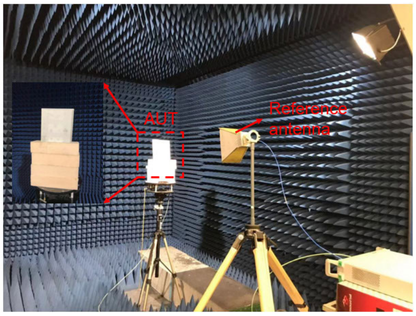

FIGURE 13. The setup for the antenna measurement.

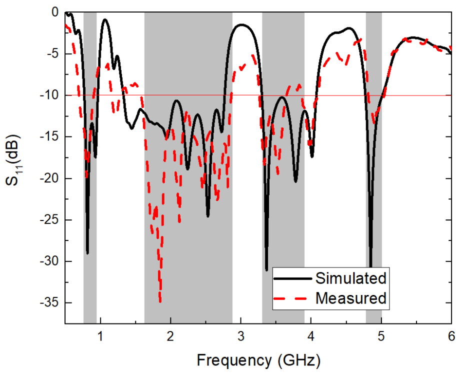

FIGURE 14. The simulated and measured reflection coefficient of the proposed quadruple-band antenna.

Fig. 16 shows the simulated and measured efficiency of the proposed antenna. The overall measured efficiency is over 80%, which is less than the simulated efficiency, which likely due to dielectric loss larger than the one used for simulation.

Fig. 17 depicts the simulated and measured co- and cross-polarized radiation pattern at the start and stop frequencies of each band in H-plane (YOZ plane) and V-plane (XOZ plane). The measured radiation patterns are in good agreement with the simulated ones. For the higher frequency band, the radiation patterns have some distortions. However, for indoor antennas, the radiation pattern requirement is not strictly for the broadside radiation.

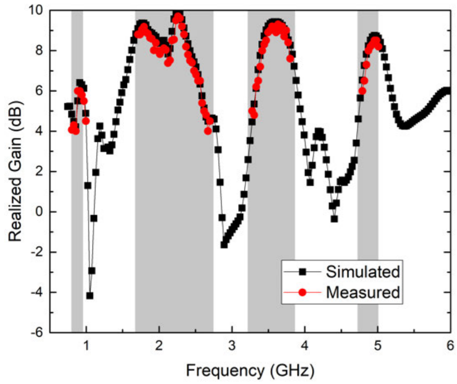

FIGURE 15. The simulated and measured maximum gain of the proposed quadruple-band antenna.

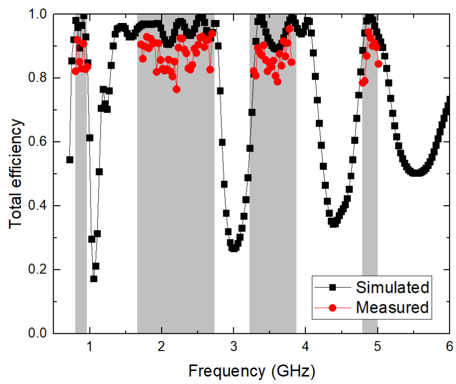

FIGURE 16. The simulated and measured total efficiency of the proposed quadruple-band antenna.

Table 2 illuminates the comparison of several multi-band antennas with the proposed antenna. Most of the reference antennas were designed for 2G/3G/4G systems; only one antenna includes the 5G band [17]. It is apparent that the proposed antenna has a relatively small size, especially the height. Meanwhile, it is also the only antenna that covers

TABLE 2. Comparison of several multi-band antennas with the proposed antenna.

Reference	Frequency band (MHz) LB	Frequency band (MHz) UB	Bandwidth (%) LB		Bandwidth (%) UB		Gain (dBi) LB	Gain (dBi) UB	Dimensions (mm^3)
[15]	800 – 960	1700 – 2700	18	(VSWR ≤ 1.5)	46	(VSWR ≤ 1.5)	4.6	8.7	220 × 220 × 42
[16]	790 – 960	1710 – 2170	19.4	(VSWR ≤ 1.5)	23.7	(VSWR ≤ 1.5)	9.5	9	255 × 255 × 130
[17]	700 - 960	1700 – 3000	31.3	(VSWR ≤ 2)	55.3	(VSWR ≤ 2)	5.5	8	220 × 220 × 100
	3300 – 3800		14	(VSWR ≤ 2)			5.5		
[24]	780 – 1100	1580 – 2620	34	(VSWR ≤ 2)	49.5	(VSWR ≤ 2)	7	8	220 × 220 × 57
[25]	800 – 980	1540 – 2860	20	(VSWR ≤ 2)	60	(VSWR ≤ 2)	8	8	360 × 280 × 45
[26]	790 – 960	1710 – 2170	19.4	(VSWR ≤ 1.5)	23.7	(VSWR ≤ 1.5)	9.3	9	255 × 255 × 71
Proposed	**770 – 960**	**1320 – 2800**	**22**	**(VSWR ≤ 2)**	**71.8**	**(VSWR ≤ 2)**	**5.4**	**8.1**	**204 × 175 × 39**
	3300 – 4100	**4790 – 5000**	**21.6**	**(VSWR ≤ 2)**	**4.3**	**(VSWR ≤ 2)**	**8.5**	**8.1**	

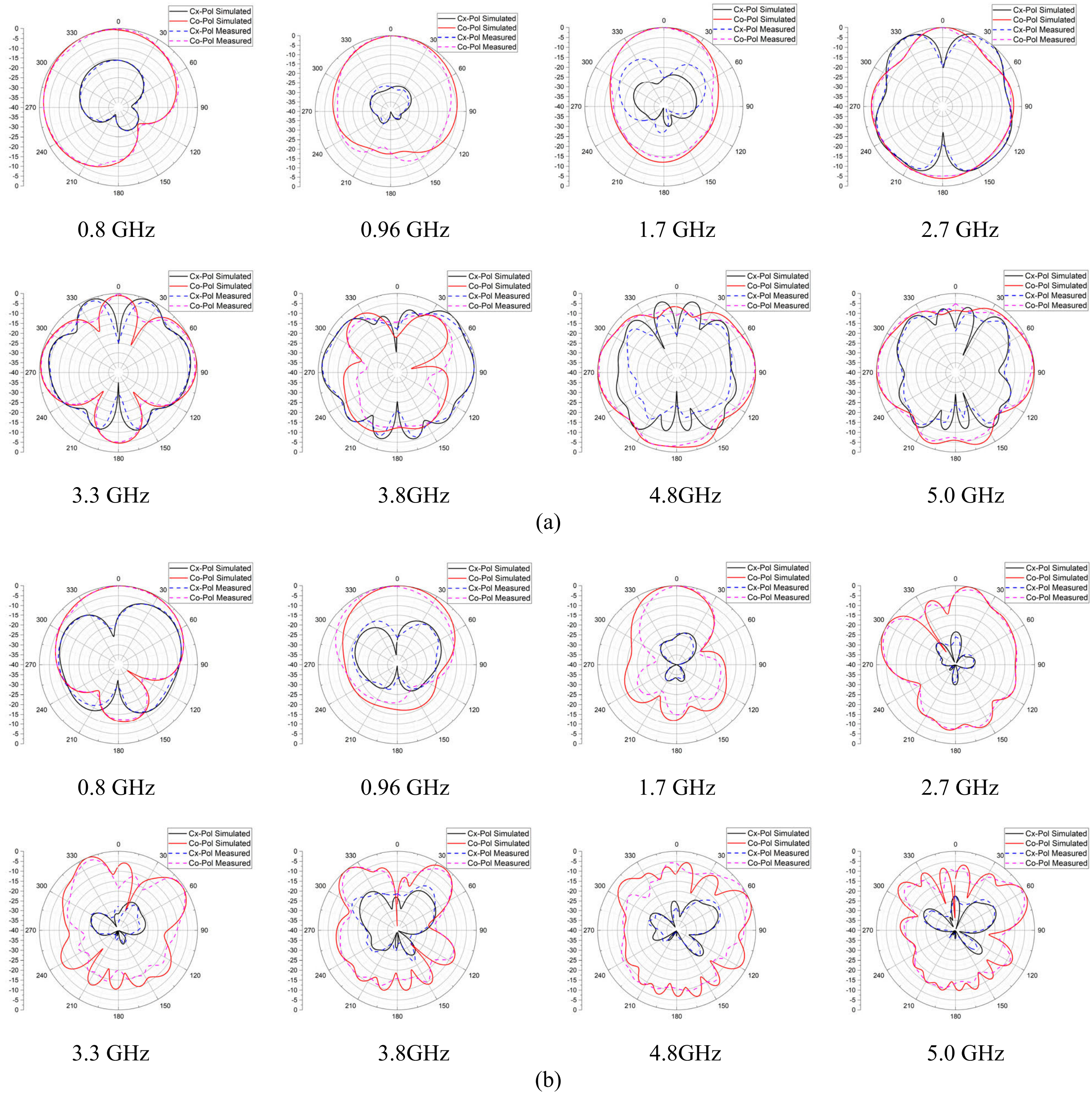

FIGURE 17. The simulated and measured co- and cross-polarized radiation pattern. (a) H-plane (YOZ plane). (b) V-plane (XOZ plane).

the four bands used for 2G/3G/4G/5G systems with a good performance.

V. CONCLUSION

A compact quadruple-band indoor base station antenna for 2G/3G/4G/5G systems has been designed, optimized, fabricated and measured. It covers four wide bands from 0.8 to 0.96 GHz, 1.7 to 2.7 GHz, 3.3 to 3.8 GHz and 4.8 to 5.0 GHz respectively. A plastic case and support frame were fabricated for the antenna to realize a sturdy structure. An asymmetrical dipole antenna and parasitic patches were employed for the lower resonant frequency bands ranging from 0.8 to 0.96 GHz and 1.7 to 2.7 GHz. The stepped impedance feeding structure was used to feed the dipole antenna and meanwhile acted as a radiator for the high frequency band of 3.3 – 3.8 GHz. In addition, a higher resonant frequency has been introduced by a small T-shaped patch to cover 4.8 – 5.0 GHz. The PSADEA method was chosen to optimize 19 critical design parameters to adjust the coupling between the small T-shaped patch and stepped impedance feeding structure. Thus, the proposed quadruple-band performance with VSWR < 2 over the frequency band of interest has been obtained. The proposed antenna has achieved low cost and lightweight through aluminum and PVC material manufacturing procedures. It also has a low profile, good performance and sturdy structure simultaneously We believe that the proposed design will be an excellent candidate for 2G/3G/4G/5G base station antenna systems. For future work, the lower band could be further extended to cover 0.7 – 0.96 GHz to make the antenna suitable for worldwide applications.

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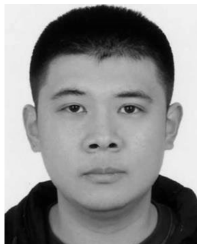

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